Title: A revised Plio-Pleistocene age model and paleoceanography of the northeastern Caribbean Sea: IODP Site U1396 off Montserrat, Lesser Antilles

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Abstract

Site U1396 was piston cored as a part of Integrated Ocean Drilling Project Expedition 340 to establish a long record for Lesser Antilles volcanism. A ~150 m sediment succession was recovered from three holes on a bathymetric high ~33 km southwest of Montserrat. A series of shipboard and newly-generated chronostratigraphic tools (biostratigraphy, magnetostratigraphy, astrochronology, and stable isotope chemostratigraphy) were employed to generate an integrated age model. Two possible chronostratigraphic interpretations for the Brunhes chron are presented, with hypotheses to explain the discrepancies seen between this study and Wall-Palmer et al. (2014). The recent Wade et al. (2011) planktic foraminiferal biostratigraphic calibration is tested, revealing good agreement between primary datums observed at Site U1396 and calibrated ages, but significant mismatches for some secondary datums. Sedimentation rates are calculated, both including and excluding the contribution of discrete volcanic sediment layers within the succession. Rates are found to be 'pulsed' or highly variable within the Pliocene interval, declining through the 1.5-2.4 Ma interval, and then lower through the Pleistocene. Different explanations for the trends in the sedimentation rates are discussed, including orbitally-forced biogenic production spikes, elevated contributions of cryptotephra (dispersed ash), and changes in bottom water sources and flow rates with increased winnowing in the area of Site U1396 into the Pleistocene.

INTRODUCTION

Montserrat Island is part of the Lesser Antilles island arc in the Caribbean Sea. The Lesser Antilles arc has a volcanic history dating back to the mid-Oligocene, though the western arc has been active since the early Miocene (Macdonald et al. 2000). Montserrat is one of the youngest islands in the arc and was subaerially built over three major volcanic centers, the oldest deposit dated to ~2,600 ka (Harford et al. 2002). The current phase of volcanism began in 1995 and at South Soufrière Hills has produced numerous volcanic deposits that range from pyroclastic material deposited on land and in the surrounding ocean, to substantial marine debris flows mapped using bathymetric surveys (Le Friant et al. 2010; Crutchley et al. 2013). Because ~65% of volcaniclastic material is transported into the ocean after an eruption (Le Friant et al. 2010), it is critical to establish a robust geologic record from detailed offshore data.

The history of Montserrat volcanism has been largely extended based on the offshore sedimentary record, and is an area of active research (e.g., Cassidy et al. 2013, 2014; Le Friant et al. 2008, 2010; Trofimovs et al. 2010; Shipboard Scientific Party 2012; Wall-Palmer et al. 2014; McCanta at al. 2015). This history also has relevance to the hazards posed by volcanic activity to the surrounding communities. Landslides, in particular, may be a source of concern as potential tsunamogenic events, because they emplace substantial amounts of material into the ocean in a short period of time, as seen both in the modern (e.g., Herd et al. 2006) and geological record (~14 ka; Trofimovs et al. 2010). Although some landslides and debris avalanches have been associated with the recent activity of the Soufrière Hills volcano (e.g., Herd et al. 2006), landslides identified in the geological record have less certain affinities and may be related to rapid sea-level rise associated with transitioning from glacial to interglacial conditions (Trofimovs et al. 2010; Coussens et al. 2016). Understanding the past history of volcanic activity

in the Lesser Antilles, and the frequency and cause of previous landslides, is therefore important for the prediction of future potential geohazards. With that in mind, Integrated Ocean Drilling Program (IODP) Expedition 340 cored three sites to examine the structure, composition, and history of the sediments surrounding Montserrat. Here, we discuss hemipelagic sedimentation from U1396, a coring site situated on a topographic high with low sedimentation rates, and where erosion is likely minimal.

During the Pliocene and Pleistocene, the Caribbean Sea was sensitive to the presence or absence of the Panamanian Isthmus, separating the Atlantic and Pacific oceans (e.g., Groeneveld et al. 2014). Precise timing and the oceanographic impacts of the Panamian Isthmus closure remains a controversial issue that has yet to be resolved (see discussion in Molnar 2008). Some authors suggest that the closure increased meridional overturning circulation in the Atlantic Ocean (e.g., Keigwin 1982; Haug and Tiedemann 1998; Osborne et al. 2014) while others suggest, for instance, a profound shift to oligotrophic waters (e.g., Chaisson 2003; Jain and Collins 2007). Although these hypotheses could be interrelated, their studies suggest differences in timing of greater than a million years.

The precision of biostratigraphic datums is generally not discussed as it is hard to quantify. As all of the data are biological, they are thus filtered through various 'noisy' processes. Planktic foraminifera, for example, are prone to ecological and climatological fluctuations, and regional distributions controlled by oceanographic processes (Bé & Tolderlund 1971), all of which can affect the stratigraphic level of highest and lowest appearances (e.g., Weaver and Clement 1986). Taphonomic processes, such as winnowing or differential preservation, for example, can also change the true 'Top' or 'Bottom' of a species. Despite

inherent difficulties, the utility and value of planktic foraminiferal biostratigraphy is well-established. Most biostratigraphic calibrations use zonation schemes divided into 'tropical' or 'tropical-subtropical', while additional subdivisions (Atlantic vs. Pacific Ocean calibrations) alleviate some of the regional differences. Wade et al. (2011) recently established and recalibrated a number of datums gathered from a variety of sources (used here: Chaproniere et al. 1994; Berggren et al. 1995; Mix et al. 1995; Chaisson and Pearson 1997). Wade et al. (2011) also used the Cande and Kent (1995) geomagnetic polarity timescale, as well as more recent astrochronologically-calibrated timescales (Pälike et al. 2006; Lourens et al. 2004) to produce robust datum ages. However, while these dates are robust at a single site or region, it is not commonplace to define an 'error' for the datums. Biostratigraphic originations, even species that are rapidly dispersed are at best only geologically instantaneous, as a species cannot arise simultaneously around the globe. Similarly, true biological extinctions are likely a series of regional extinctions that finally culminate in the complete elimination of the entire species. One reason that planktic foraminifera persist as a premier biostratigraphic system is due to their wide, and largely homogenous, biogeographic ranges (Bé & Tolderlund 1971). Thus, their 'regional' originations and extinctions occur at the scale of tropical-subtropical subdivisions.

IODP Site U1396 (Figure 1) presents an ideal locality to test the last 4.5 myr of the Wade calibration. Shipboard analysis suggests that the sediments from Site U1396 represent relatively continuous sedimentation and an excellent paleomagnetic stratigraphy was recovered (Expedition 340 Scientists 2013). Shipboard planktic foraminiferal and nannofossil biostratigraphic analyses determined that all primary datum species, and the majority of the secondary datum species, were present at the site. Detailed shipboard core descriptions

established lithologic units splitting dominantly hemipelagic sedimentation from disturbed or large volcaniclastic units (Expedition 340 Scientists 2013).

The aim of this study is twofold. The first is to produce a robust age-model at or near the marine isotope stage resolution. Although the recovered sediments cannot address early aspects of the Panamanian Isthmus closure history, which began in the Miocene (Keigwin 1982; Duque-Caro 1990; Haug and Tiedemann 1998), it can address questions about the final closure (~4.2-2.5 Ma; Keller et al. 1989; Haug et al. 2001) and the impacts on the biota, productivity, and circulation with the Caribbean Sea (e.g., Kameo and Sato 2000; Chaisson 2003; Jain and Collins 2007). The ~150 m cored deposits at Site U1396 represent 4.5 myr of sedimentation. We built a new robust age-model to address these questions.

Second, this site presents a good opportunity to test the newly-recalibrated datums from Wade et al. (2011). To this end, several chronostratigraphic tools were employed. Astrochronological tuning was performed on the color reflectance parameter L* (Brightness) from shipboard physical properties data using the 'astrochron' package within the R programming environment (Meyers 2014; R Core Team 2015). A ~9-kyr resolution benthic foraminiferal $\delta^{18}O$ record was generated and compared to the LR04 benthic foraminifera stack (Lisiecki and Raymo 2005). Planktic foraminiferal biostratigraphy was also carried out at the same resolution (~9 kyr), to provide support for the other chronostratigraphic techniques and to be checked against the calibrations.

REGIONAL SETTING AND SHIPBOARD RESULTS

Site U1396 is located at 16°30.49′N, 62°27.10′W at ~800 m water depth. It is roughly southwest from the island of Montserrat sitting atop a bathymetric high. Coring at this site was hypothesized to limit the occurrence of turbidites, allowing for a more continuous record of volcanism than possible in other areas offshore of Montserrat. In addition, the sedimentation rates determined for the nearby CARMON-2 site (Le Friant et al. 2008) suggested it would be possible to extend the existing geologic history to 4-5 Ma (Expedition 340 Scientists 2013). Three holes were cored at Site U1396 using advanced piston coring. Holes U1396A and U1396C each consist of 15 cores and are continuous over 135 m and 140 m, respectively, whereas Hole B is a single 10 m core taken to replicate 340-U1396A-2H which suffered a shattered liner during coring. Lithostratigraphy between the holes correlates well (see below), excluding a single interval which contained a substantial amount of basal flow-in of pumiceous sand (Jutzeler et al. 2014), which does not occur over the same thickness in U1396A. Shipboard age determination suggested that the base of U1396C was older than U1396A, so U1396C was selected as the main hole for biostratigraphic and stable isotope study.

METHODS

Depth scales and shipboard data

Description of the core, preliminary calcareous nannofossil and planktic foraminiferal biostratigraphy, and physical properties data collection (e.g., color reflectance) were all performed onboard the R/V *JOIDES Resolution* during IODP Expedition 340. The initial shipboard age model and resulting sedimentation rates for the Pliocene (~4 cm/kyr) and Pleistocene (~2 cm/kyr) were determined by the paleomagnetic reversal stratigraphy and

supported by nannofossil and planktic foraminiferal biostratigraphy (Expedition 340 Scientists, 2013). A composite depth scale (CCSF-A) was generated with a primary splice (CCSF-D) (Hatfield 2015). The CCSF-D record relies heavily on core sections from Hole U1396A, in part because it is the most complete record as two 10-cm whole rounds were consistently taken from each Hole C core shortly after core recovery. A tool was created in the R computing environment (R Core Team, 2015) to place off-splice data and all preexisting and newly-generated data into the CCSF-D scale. Figure 2 depicts the process of splicing the color reflectance data and lithostratigraphic data from the initial CSF depth scale to the CCSF-A depth scale, and finally onto the continuous splice. The L* (brightness) and lithostratigraphy data sets both agree well with the magnetic susceptibility based correlation of Hatfield (2015), indicating the compositing process is robust (Figure 2b). We use the revised assessment of the paleomagnetic reversal record here (Hatfield 2015) rather than the one generated shipboard. Hatfield (2015) did not correlate Core 340-U1396A-2H into the composite section due to issues with the magnetic susceptibility record of the disturbed core. Using both the core description and core photos of Cores 340-U1396A-2H, U1396C-1H, and U1396C-2H we now place 340-U1396A-2H on the U1396A CCSF-A scale using an offset of 1.71 m based on lithostratigraphic correlation.

Generation of an 'Event-Free' section

Volcanic sedimentation derived from eruption (syn-eruptive *sensu* Carey and Schneider 2011) is geologically instantaneous. Ash deposits, for example, are frequently darker in color than hemipelagic material, and so impart stochastic noise (from a cycle perspective) to an

analysis of the expected cyclic bands of sediment produced by Milankovitch or glacial-interglacial periodicity. Also, hemipelagic material is deposited at a different, quasi-continuous, sedimentation rate relative to the 'instantaneous' ash deposits. Removal of the discrete volcanic deposit intervals, such as ash beds, should result in a cleaner hemipelagic stratigraphic column, and potentially a series of Milankovic-style frequencies that are less dominated by noise. However, this does not alleviate the issue of dispersed ash, as documented by ODP Leg 165 in the Caribbean (Sigurdsson et al. 1997) and within the upper several meters of Hole U1396C (McCanta et al. 2015). An R function was employed to remove the volcanic sediments from the stratigraphy. The function employs the shipboard core description to identify the various sediment types with a major lithology type of volcanic origin, and then removes their thicknesses from the stratigraphy. The explicit assumption made here is of no erosion during any 'event'. It then recalculates the depths for the remainder of the stratigraphy as if the volcanic sediments were not there resulting in a CCSF-NV (No Volcanics) scale (Figure 2 depicts this process). The CCSF-NV scale allows the comparison of three distinct sedimentation rates: composite (hemipelagic+volcanic), hemipelagic, and volcanic.

Astrochronological tuning

Astrochronology is a method of age determination that employs the known frequencies of various astronomical parameters (e.g., obliquity) and some high-resolution dataset, in this case sediment brightness, to derive an age model. Astrochronological tuning of the sedimentary record from Site U1396 was not done independently of other age diagnostic criteria. Instead, approximately half the paleomagnetic datums were used to generate a hemipelagic

sedimentation rate (linear sedimentation rate without the thickness of volcanically-sourced sediments). Astrochronological analysis was then performed using 'astrochron', a package developed for R (Meyers 2014). Tuning was performed in intervals ~0.5 myr in length. L* was interpolated to 3-kyr intervals, prior to the evolutive harmonic analysis (EHA). The stratigraphic sequence was padded to approximately double the number of points in the interpolated dataset. The window size for the EHA was 140-kyr with a step of 3-kyr. EHA results (e.g., figure 3) suggest the presence of tunable frequencies, despite the still substantial component of noise.

Tuning was performed so that there was as good an agreement between age diagnostic criteria and orbital or glacial-interglacial frequencies as possible, but, as previously noted, the signal is still prone to substantial noise due to data interpretation, core recovery, and sedimentological factors; for example, a slight offset in the splice correlation could result in a missed portion of a cycle at splice points. If the sedimentation rate were 4 cm/kyr, an offset in the splice of 2.5 cm would result in a loss of ~1/4 of the 41-kyr obliquity cycle. This would manifest in the EHA diagram by splitting the observed frequency into two pieces, one higher frequency and one lower, with a gap in the middle (Meyers and Sageman 2014). It is also possible that removing all volcaniclastic beds is overly cautious; some of those sediments may not be geologically instantaneous and may be from redeposition of volcanic components (post-eruptive *sensu* Carey and Schneider 2011). The presence of cryptotephra (dispersed ash) changes the L* value of the sediments away from the predicted orbital or glacial-interglacial pattern, and increases the bed thickness. The wide window (140-kyr) accounts for this increase in noise, but it induces a lag. An example of this effect is the smearing of frequencies around the

interpreted paleomagnetic datums. In Figure 3 the white lines above and below the black anchor datum are where the EHA begins to record a change in sedimentation rate; the smearing is a result of the change from one linear sedimentation rate to the next. The window size was a compromise between accounting for this noise and creating an age model responsive to sedimentation rate changes.

Micropaleontologic Methods

A total of 596 samples were examined for biostratigraphically-important species. Two different strategies were used for sample choice. Within the upper 7 m of Site U1396, a sample spacing of 5 cm (~0.5-2 kyr) was used (these samples were previously used in Wall-Palmer et al. 2014). Below 7 mbsf a sampling resolution of ~9 kyrs was used, based on the shipboard age model, but excluding volcanic sediments. All samples were checked against the Jutzeler et al. (2016) coring disturbance compilation and were found to be outside of all intervals with coring disturbances. For samples below 7 meters, samples were dried for ~24 hours, then soaked in a mild Sparkleen® solution for 24-72 hours, a step necessary to free foraminifera from surrounding sediment. Sediment was washed over a 63 µm sieve before being dried for ~24 hours in a 40-50°C oven. Prior to being inspected, samples were dry-sieved over a 150 µm sieve. All identification was performed at the >150 µm size fraction, following the taxonomy of Kennett & Srinivasan (1983), though with consideration of remarks by Chaisson and Leckie (1993), Chaisson and Pearson (1997), Pearson (1995), and Spezzaferri et al. (2015). Variability within the illustrated species in Parker (1962) was also considered. Ages for the biostratigraphic datums follow the Wade et al. (2011) astrochronological calibration (and references therein).

Samples within the upper Pleistocene-Holocene Brunhes chron were inspected for *Globorotalia menardii* and *G. tumida*, as the abundances of those taxa have been shown to fluctuate in response to glacial-interglacial cycles (e.g., Ericson and Wolli 1968; Kennett and Huddlestun 1972). This biozonation scheme has been employed globally and locally with success (e.g., Reid et al. 1996). Here it was used to continue the data collection of Wall-Palmer et al. (2014), extending their record of %*G. menardii-tumida* (undifferentiated) to the first geomagnetic reversal (i.e., base of the Brunhes chron). Following the Wall-Palmer et al. (2014) methods, samples were dry-sieved over a 355 µm sieve, then a split to ~300 individuals was performed using a microsplitter. Total planktic foraminifera and *G. menardii-tumida* tests were counted.

Individual foraminifera from near the top or bottom of their range were imaged on a Carl Zeiss EVO 50 XVP scanning electron microscope to corroborate the positions of the datums described within this work. The selected foraminifera were placed on a piece of carbon tape, and then coated with a 4 nm thick coating of carbon or platinum prior to imaging.

Stable isotope analysis

Three species of benthic foraminifera (*Planulina wuellerstorfi, Cibicidoides mundulus,* and *Cibicidoides robertsonianus*) and one species of planktic foraminifera (*Globigerinoides ruber*) provide a stable isotope chemostratigraphy for Site U1396. *P. wuellerstorfi* was most common until 25 m CCSF-A (~1.5 Ma), although it was absent in some samples throughout this interval. In these cases, *C. mundulus* was used in place of *wuellerstorfi,* but within the upper ~10 m *mundulus* was also scarce, and *C. robertsonianus* was used instead. Within the top 7 m, sample

volume was reduced (to alleviate the depletion of the core with the 5-cm resolution), and so a mixture of all three species was used. *Globigerinoides ruber* was used through the Brunhes chron to address low variability within the benthic $\delta^{18}O$ record (see below).

Preservation state was variable through the study interval. Specimens were graded on a 'glassy' - 'frosty' - 'bad' scale. Glassy individuals were transparent, with no infilling. Frosty individuals were opaque, or had mild infilling. 'Bad' individuals, which were only used in rare instances where there was no other choice, had overgrowths, broken final chambers, or moderate infilling. The best-preserved individuals were used for isotopic analysis, though tests were generally 'frosty' throughout the study interval. A table of $\delta^{18}O$ values, ages, species, and preservation grade can be found in the supplemental information. The only general trend identified in preservation was a gradual decrease in the frequency of well-preserved benthic foraminifera with increasing depth, though examples of good preservation were found near the base of Site U1396.

Planulina wuellerstorfi was typically used in preference to either *Cibicidoides* species. Forty-one samples contained sufficient individuals from two species to allow isotopic offsets to be generated between the species. The number of individuals analyzed in each sample varied (see supplemental information), but was typically only three to four, due to the large mass of the benthic tests. Approximately nine individuals of planktic *G. ruber* were used in each analysis. The majority of samples were run at the University of Massachusetts-Amherst Stable Isotope Laboratory on a Finnigan Delta XL+ with a Kiel III automated carbonate preparation system (>7 mbsf; these are in black, red, and brown on Figure 4). All data are reported in delta notation against the VPDB standard. Replicated analyses of UMass house standard material

have a 1σ error of 0.08‰ $\delta^{18}O$. The rest of the samples were run at the National Oceanography Centre, Southampton using a Europa GEO 20-20 mass spectrometer with an automatic carbonate preparation system (0-7 mbsf; orange on Fig. 4).

RESULTS

Astrochronology

Brightness (L*) in the shipboard color reflectance dataset (Expedition 340 Scientists 2013) was found to have cyclicity on orbital periods (Fig. 3), despite noise present outside of the expected orbital signals. Tuning resulted in mild offsets from the sedimentation rate derived from linearly interpolating between paleomagnetic reversals, and there appears to be a continuous record of sedimentation at this site. It should be noted that tuning was performed attempting to fit all available chronostratigraphic information and the results of Wall-Palmer et al. (2014) (See 5. Discussion). Most of the deviations from paleomagnetically-derived ages are within the 0-50 kyr range.

Benthic isotope values

Stable isotope results largely agree with the expected general pattern of glacial-interglacial cycles, with variability decreasing with depth. There is a gradual trend towards increasing $\delta^{18}O$ values, with a mean value of ~2‰ for 100-150 CCSF-A, increasing to ~2.5‰ for 50-10 CCSF-A. Strong (>1‰) variability in the record is seen beginning around 30 mbsf until 0 mbsf, with a marked step towards higher values observed at ~80 CCSF-A.

The offset in $\delta^{18}O$ values between the three species was calculated (Figure 5). Most $\delta^{18}O$ offsets were within the propagated instrumental error for the two $\delta^{18}O$ measurements (~0.1‰ for each measurement, and therefore ~0.14‰ for offsets). The mean offset between *Planulina wuellerstorfi* and *Cibicidoides mundulus* was ~0.062‰ (n=25), while *Cibicidoides mundulus* and *Cibicidoides robertsonianus* was ~-0.011‰ (n=14). Only two samples contained both *Planulina wuellerstorfi* and *Cibicidoides robertsonianus,* and they displayed a mean offset of -0.105‰. No stratigraphic trends were noted with respect to the offsets.

Planulina wuellerstorfi was most commonly used within 150-80 CCSF-A, with *Cibicidoides mundulus* and *C. robertsonianus* largely used until ~7 mbsf, and, due to smaller sample sizes, a mix of benthic all three species above 7 mbsf. When *P. wuellerstorfi* was not available (above 80 CCSF-A), *Cibicidoides mundulus* was used to supplement, using the offset value generated in this study (~0.062‰). In the case where *Cibicidoides roberstonanius* was the only possible choice, the offsets from *P. wuellerstorfi* to *C. mundulus* and *C. mundulus* to *C. robertsonianus* were used to calculate the composite value (green line, fig. 5A).

Benthic foraminiferal $\delta^{18}O$ results follow the trends established by the LR04 benthic foraminiferal stack (Lisiecki and Raymo 2005). Although the sampling resolution within this study is lower than that of Wall-Palmer et al. (2014), similar trends can be identified between the planktic and benthic $\delta^{18}O$ records. Figure 4 presents the correlations between the astrochronologically-derived ages and the LR04 stack (grey lines). Several intervals were not correlated, mainly due to data-resolution issues, but also due to the obscuring of MIS cycles through other means (see discussion about low benthic $\delta^{18}O$ variability below). Those include

around MIS 55 (~1.6 Ma) and around KM2 (~3.1 Ma). There are also several suggested changes to the interval correlated by Wall-Palmer et al. (2014), which are discussed below.

Biostratigraphy

The majority of the datums from Wade et al. (2011) were found within the sediments at Site U1396 (Table 1, Figure 6). Only *Globorotalia hirsuta*, *Globoralia hessi, Globorotalia excelsa, Globoturborotalia apertura, Globoturborotalita woodi,* and *Globoturborotalita decoraperta* were not found, or were found in such sporadic occurrences they had limited biostratigraphic utility. *Pulleniatina* was not split into distinct species, instead only the presence or absence of *Pulleniatina* spp. was noted. The order of primary datums was found as expected from youngest to oldest: Top (T) *Globorotalia tosaensis,* T *Globigerinoidesella fistulosa,* T *Globorotalia miocenica,* T *Dentoglobigerina altispira*, T *Sphaeroidinellopsis seminulina*, T *Globorotalia margaritae*, and lastly T *Globoturborotalita nepenthes. Globigerinoidesella fistulosa* was found only sporadically and was found above the expected range by ~0.5 Myr. *Globorotalia tosaensis* has only a ~100 kyr difference between the U1396 top and the calibrated age, but otherwise the few biostratigraphic species within the Pleistocene are found well outside their expected ranges (see 5. Discussion). Within the Pliocene, the ranges of *G. miocenica, D. altispira, S. seminulina, G. margaritae,* and *G. nepenthes* all fit very closely to their expected ranges as calibrated by Wade et al. (2011).

Secondary datums T *Globigerinoides obliquus*, T *Globorotalia exilis*, Base (B) *Globorotalia truncatulinoides*, T *Globorotalia limbata*, T *Globorotalia pertenuis*, B *Globorotlia tosaensis*, B *Globorotlia miocenica*, T *Globorotalia plesiotumida,* and B *Globorotalia exilis* were all found close to their calibrated ages. The bioevents Reappearance and Disappearance of *Pulleniatina* were also

extraordinarily close to their calibrated ages. In particular, several of the menardellid species (e.g., *G. exilis*) record substantial fluctuations in their populations, so their adherence to the calibrated ages is surprising, but a positive indicator of the robustness of the planktic foraminiferal datums.

Several secondary datums, as might be expected, did not conform as precisely to the expected ages. Both *Globorotalia flexuosa* datums were outside their expected range; T *Globorotalia flexuosa* was observed in the top sample, and its base (B *G. flexuosa*) was found ~1.3 myr earlier than expected. The local top for *G. extremus* was 800 kyr younger than it was expected. T *Globorotalia multicamerata* s.s. was found ~50 kyr from the predicted age, but see below for a discussion. B *G. miocenica* appears within the U1396 sediments ~200 kyr older than its calibrated age, while B *G. pertenuis* appears 500 kyr older than the calibrated base. T *Sphaeroidinellopsis kochi* occurs ~300 kyr younger than the calibrated age.

Hiatuses

Shipboard chronostratigraphy suggested a gradually decreasing sedimentation rate from the Pliocene through the Pleistocene and Holocene (Expedition 340 Scientists 2013). It also suggested a largely continuous section, without apparent hiatuses. Biostratigraphy largely agrees with the paleomagnetically-derived sedimentation rates. Clustering of biostratigraphic datums, as would be characteristic of a hiatus, is not observed in the U1396 sequence. Although hypothetically evolutive harmonic analysis can be used to identify hiatuses (Meyers and Sageman 2004), the use of such a large window (140-kyr) and the amount of noise within the signal makes this impossible at Site U1396. Astrochronology suggests that there are instances of lowered sedimentation rate. In the absence of strong evidence for hiatuses, the U1396 benthic

and planktic $\delta^{18}O$ isotope time series was correlated to marine isotope stages as if there were no hiatuses.

DISCUSSION

Brunhes stratigraphy

This study continues much of the data collection begun in Wall-Palmer et al. (2014). In doing so, some conflicting age diagnostic criteria were revealed within tens of cm from the base of the Wall-Palmer study, suggesting a revision of that chronostratigraphy may be necessary. For example, Wall-Palmer et al. (2014) used a %*Globorotalia menardii-tumida* zonation scheme (Ericson and Wollin 1968; Kennett and Huddlestun 1972) successfully employed in the region (e.g., Reid et al. 1996; Le Friant et al. 2008). This scheme relies on the relative abundance of *Globorotalia menardii* or *Globorotalia tumida* (the majority of the flat, keeled planktic foraminifera within these sediments). The zonations are described as abundant (in zones Z, X, V, and T) or not abundant (zones Y, W, and U). Distinguishing between 'abundant' and 'not abundant' is not always obvious in these sediments (Figure 7, W to early V). Here we continued the %*G. menardii-tumida* counts down to the Brunhes-Matuyama reversal, identifying distinct proportion changes centimeters below the lowest sample analyzed by Wall-Palmer et al. (2014). This extension of %*G. menardii-tumida* data, as well as the longer perspective of the entire Brunnes chron, creates uncertainty for some aspects of the chronostratigraphy of Wall-Palmer et al. (2014).

The most important chronostratigraphic control used by Wall-Palmer et al. (2014) in the lower part of their study interval was the base (B) of *Emiliana huxleyi* (Figure 7). B *Emiliana*

huxleyi globally occurs within MIS 8 (~0.27 Ma) or MIS 9 (~0.29 Ma; Ogg et al. 2014). It was identified at ~6.9 m with SEM imaging (Wall-Palmer et al. 2014), but other studies (Aljahdali 2013, unpublished Masters Thesis, Florida State University) place the first occurrence much higher (~3 m). In addition, the planktic foraminifera datum for Biozones PT1a/1b, T *G. tosaensis* (~0.61 Ma; Wade et al. 2011), was determined to be slightly below the *E. huxleyi* datum. Within the original publication, this was suggested to be a regional difference in extinction, with T G. *tosaensis* occurring at MIS ~8 (0.27 Ma), which is ~340 kyr offset from its calibrated age (Wade et al. 2011). It should be noted that several species discussed later have large offsets from the Wade et al. (2011) biozonation scheme at this site.

The following discussion highlights the discrepancies noted within the Brunhes chron (Figure 7). However, the stratigraphy presented in Wall-Palmer et al. (2014) is largely convincing when directly compared with previous studies within the area (Le Friant et al. 2008; Trofimovs et al. 2010). Despite the comparatively low resolution of the new benthic and planktic foraminifera oxygen isotope stratigraphy presented here, the longer perspective of this study highlights discrepancies that are not apparent in those previous studies, which all focus on the uppermost, <~250 kyr seafloor sediment. In addition, oxygen isotope values from MIS 3 to MIS 4 in Wall-Palmer et al. (2014) rise when most records (e.g., Martinson et al. 1984; Lisiecki and Raymo 2005; Le Friant et al. 2008) demonstrate lowering values. There is also a prominent negative shift within MIS 6 (~2‰), when global records (e.g., Martinson et al. 1984; Lisiecki and Raymo 2005) are largely constant. That shift which was correlated to a negative shift in the CAR-MON 2 record (Le Friant et al. 2008), but the magnitude at CAR-MON 2 was only ~1‰. In

addition, at CAR-MON 2, the MIS 3 to 4 values when correlated with the global stack, rather than the apparently aberrant changes seen in the Wall-Palmer et al. (2014) correlation.

There is an additional unsatisfactory correlation in regards to the %*Globorotalia menardii-tumida* zonation. In figure 7, the orange bands are zones which should have higher %*G. menardii-tumida,* whereas white zones should be lower. Although there is a slight shift at the CAR-MON 2 X Zone to younger ages, the zonal boundaries and abundances are largely as expected (Le Friant et al. 2008), suggesting that a good fit is possible within the region. Within the Wall-Palmer et al. (2014) scheme the divisions between various zones conform poorly to the expected zonation scheme (Fig. 7). For example, Zone X, which should be 'high abundance' has lower abundance on average than Zone W, which should be 'low abundance'.

Three possibilities may explain the observed discrepancies (B *E. huxleyi,* T *G. tosaensis*, $\delta^{18}O$ magnitudes, and %*G. menardii-tumida*). First, if the revised stratigraphy proposed in Fig. 7 is incorrect and the Wall-Palmer et al. (2014) stratigraphy is correct, the Aljahdali datum (B *E. huxleyi*) is 3 m too high, and there is a condensed section encompassing MIS 9 to 13. This then suggests that MIS 3 has a $\delta^{18}O$ value roughly equivalent to MIS 5 or 7, rather than the much more positive value expected (Martinson et al. 1984; Lisiecki and Raymo 2005). Although some differences could be attributable to local effects (sea surface temperature or salinity), because these values are derived from the mixed-layer dwelling *G. ruber*, the values from CAR-MON 2 are similar to those expected (Le Friant et al. 2008). As described above, MIS 6 (as identified by Wall-Palmer et al. 2014) also has a 'spike' of double the magnitude observed elsewhere. Also, the %*G. menardii-tumida* zonation then has a much weaker connection to the glacial-interglacial cycles. In addition to the previously described difficulties in Zones Y-W, the predicted high

abundances through zone V are entirely absent. This is in direct opposition to the CAR-MON 2 core, where the expected higher values for Zone X are present (slightly later than expected, however), whereas the low absence that defines Zone W is typified by 0%, rather than the increase of ~3-4% observed in the Wall-Palmer et al. (2014) correlation. Despite the poor chronostratigraphic fit described above, it should be stated that B *E. huxleyi* is an exceptionally well-established datum, with a consistently robust MIS 8 appearance within the tropics (Thierstein et al. 1977; Ogg et al. 2012), and as such, should have a higher chronostratigraphic priority than a comparably less precise abundance-based zonation scheme. There are lithostratigraphic correlations that appear to support the Wall-Palmer et al. (2014) chronostratigraphic correlations (Coussens et al. 2016), but they lack the longer time-series present at U1396.

Second, if the Wall-Palmer et al. (2014) datum is valid and the Aljahdali datum is incorrect, and the rest of the Wall-Palmer et al. stratigraphy is not correct, then this would represent a >100 kyr earlier origination for *E. huxleyi* than previously identified. As stated above, B *E. huxleyi* has a remarkably globally synchronous first appearance at MIS 8 (Thierstein et al. 1977), whereas the Wall-Palmer stratigraphy suggests it occurred within MIS 13. This scenario to solve the discrepancy seems unlikely. A possible explanation for the *E. huxleyi* datum presented by Wall-Palmer et al. (2014) may be due to downhole contamination, making the Aljahdali B *E. huxleyi* datum the first *in situ* occurrence (MIS 8; Thierstein et al. 1977; Ogg et al. 2012). The sample cited for the B *E. huxleyi* by Wall-Palmer et al. (2014) (Sample 340-U1396-1H-5, 90-91 cm) only contained rare *E. huxleyi*, while the only other samples examined above (Samples 340-U1396-1H-1, 1-2 cm and 340-U1396-1H-1, 30-31 cm) contained abundant *E.*

huxleyi. While the sediments used for SEM analysis were procured in the proper fashion (sample edges were trimmed to minimize down-hole contamination, for example), the rarity of *E. huxleyi* within Sample 340-U1396-1H-5, 90-91 cm possibly suggests that they were not in situ. This could account for the ~3 m difference between the two studies.

By removing the Wall-Palmer et al. (2104) B *E. huxleyi* control on the chronostratigraphy, we can then fit to several other chronostratigraphic systems to these observations (Figure 7). For example, *G. menardii* Zones X and V now fit with their expected abundances (Fig. 7) and MIS 6 no longer has a negative $\delta^{18}O$ excursion (MIS 6.4 in Wall-Palmer et al. 2014). Instead, that double peak has been moved to the expected position in MIS 7 and B *Globorotalia tosaensis* also has a smaller offset to the calibrated age (Table 1). It should be noted that this revision uses data that was excluded from Wall-Palmer et al. (2014) because it was within event bed B1/2. There are a greater number of keeled foraminifera within this flow, as seen within the X Zone defined by this study (~25%, Fig. 7). It is difficult to explain the preferential incorporation of keeled, thermocline-dwelling planktic foraminifera (from ~5% up to ~25%) within a bioclastic flow sourced from shallower depths, where those taxa are rare to absent. In fact, the opposite should be true, and shallow-dwelling benthics and mixed-layer planktic foraminifera should overwhelm the *G. menardii* and *G. tumida* percentages, making them even rarer. Additionally, this would be during a time interval when those taxa are especially uncommon. Very different hydrographic properties, however, between the keeled and non-keeled make it possible for this apparent anomaly to be due to some sort of sorting phenomena related to the flow. The remainder of this work employs this last hypothesis (fig. 7) as the age model. Despite this

interim conclusion, the interval between MIS 9-13 remains unsatisfactory due to the limited isotopic variation (although a hypothesis to explain this observation is discussed later).

Biostratigraphy

Relative to the calibration of Wade et al. (2011), very few of the Pleistocene datums at Site U1396 were found where they were expected. *Globorotalia tosaensis* and *G. obliquus* appear to have a robust calibration from the Caribbean perspective, but this may be a function of the limited number of datums within the Pleistocene, relative to Pliocene. Both of the youngest datums, T *Globorotalia flexuosa* and B *G. calida*, appear to have substantially different ranges than the Wade calibration. For B *G. calida*, this is possibly due to regional differences between the Pacific Ocean (the source of the Wade calibration is from DSDP Leg 135; Chaproniere et al. 1994) and the Caribbean Sea. A range of morphological variability in *G. calida* was seen at this site, which made determining the precise difference between these two similar taxa difficult. It is difficult to say then, if the misfit here is due to difficulty in differentiating an adult *G. calida* from a juvenile *G. aequilateralis* or if *G. calida* has substantially different range at this site. *Globorotalia flexuosa* is also found far earlier than expected, which has also been noted at other sites (see Robinson et al. 2016 and references therein for a discussion). The diagnostic feature of *G. flexuosa* is a ~90° twist on the final chamber, with the rest of the gross morphology resembling an intermediate form between *Globorotalia menardii* and *Globorotalia tumida.* Figure 6 (green box) depicts *G. tumida* and *G. flexuosa,* from the sample containing B *G. flexuosa.* Also within that sample, very rarely, was an aberrant form of *G. flexuosa* or *G. tumida* with a final chamber appearing to start at 90° to the coiling axis, then twisting back equatorially. This could

speculatively be seen as evidence that the '*G. flexuosa*' form is a simple mutation from the *Globorotalia tumida* sensu stricto, which induces a ~90° torsion in the final chamber, rather than being a true biological species. Further work could elucidate if there is an ecological affinity to the '*G. flexuosa*' form, or if it has a stochastic appearance in the fossil record, as would be expected of a random mutation of the form. Both of these species, *G. flexuosa* and *G. calida,* have recognition issues as they progress through ontogeny. An adult *G. calida* resembles a juvenile *Globigerinella aequilateralis,* with only modest differences in shape. *G. flexuosa,* meanwhile, is easily defined but without the final chamber could be identified as a *G. tumida.* As impoverished as the Pleistocene is for planktic foraminiferal datums, these are still poor characteristics for biostratigraphic marker taxa.

These two biostratigraphic taxa were used repeatedly shipboard during Exp. 340, because the majority of the sites recovered were younger than any primary planktic foraminifer marker datum, and so these secondary datums had to be regularly employed. Finding these two taxa outside of their expected ranges at Site U1396 calls into question many of the foraminifera-derived biostratigraphic ages for other sites drilled during Exp. 340. Many of those other sites, however, also have nannofossil biostratigraphic datums. Those ages, which were supported by the B *E. huxleyi*, the nearest nannofossil datum to B *G. calida* (calibrated age), are still considered to be reliable under this study.

There are comparatively many more datums within the Pliocene than the Pleistocene that conform to expectations. Closest to the Pliocene/Pleistocene boundary is B *Globorotalia truncatulinoides*, which might better be employed as the PL6/PT1b zonal marker than T *Globigerinoidesella fistulosa.* The difference between the Pliocene/Pleistocene boundary and the

top of PL6 would only change ~120 kyr, and *G. truncatulinoides* is more common, at least in these sediments, than *G. fistulosa.* Both taxa are easily recognizable, *G. truncatulinoides* from *G. tosaensis* by the development an imperforate band (Chaisson and Pearson 1997), and *G. fistulosa* from *Trilobatus sacculifer* by the multiple digitate projections on multiple chambers (Kennett and Srinivasan 1983). The only advantage that *G. fistulosa* has over *G. truncatulinoides* is that the projections from a *G. fistulosa* test are readily identifiable even when broken. The imperforate band identifying *Globorotalia truncatulinoides* was verified in SEM. Preservation within the base occurrence sample was good, allowing identification without a worry of diagenetic overgrowth. Both these datums were originally calibrated from ODP Site 925 (Chaisson and Pearson 1997), which has an orbital stratigraphy, though due to proximity to the equator it lacks a paleomagnetic record. Given the excellent chronostratigraphy at Site 925 and Site U1396, as well as the simple identifications of these species, this misfit seems to not be within the data or calibration, rather the uncertainty within first or last appearance itself.

Most of the menardellid Top calibrations were accurate at U1396. There is, however, an important comment about *Globorotalia multicamerata.* There are a number of *Globorotalia miocenica* at this Site that have additional chambers over the typical 6-7, and possess a more lobulated outline. They can be distinguished from *G. multicamerata* by the highly vaulted umbilical side and generally a less robust keel. This *Globorotalia miocenica* aff. *multicamerata* form goes extinct ~400 kyr after the predicted T *Globorotalia multicamerata* datum. In general, the spacing between menardellid bioevents at U1396, however, was condensed, all taking place within chron C2r. The B *G. fistulosa* occurs later than expected, and within the wrong biozone. This species is very sporadic throughout its entire range (including the upper portion of the

range), making both the first and last occurrences uncertain. The T and B *G. exilis* datums were observed in close proximity to the expected age, though not always within the biozone expected, due to deviations in other marker taxa.

Sedimentation

age scheme mismatch

This study employs three different age models: a paleomagnetic reversal record, an astrochronologically-tuned record (between paleomagnetic datums), and marine isotope stage correlations. These different methods have individual strengths and weaknesses. Paleomagnetic reversal ages are precisely known and are relatively well defined in the U1396 record (Hatfield 2015), but during periods of stable polarity the age model is a simple linear interpolation between reversals. Astrochronology provides variable accuracy and precision. The analysis utilizes a number of different parameters, like window size or interpolation step, that all change how responsive the resulting age model is to hiatuses or changes in sedimentation rates, or the upper and lower limits of detectable frequencies. Lastly, MIS correlation is generally precise provided that all marine isotope stages are present and confidence in the result is increased when constrained by the paleomagnetic reversal record. It also has the advantage, if the data-resolution is high enough to detect them, that extremely abrupt sedimentation rate changes can be observed. The same hypothetical abrupt sedimentation rate would be missed by paleomagnetic ages if it were within a single normal or reverse chron. Similarly, the change in sedimentation rate would be smoothed by astrochronology if the window size were not small enough to detect it. However, if all marine isotope stages are not present, or if data density is

poor, then correlation becomes less accurate using this method. Because of the three different characteristics of these age models, it is possible to demonstrate the advantages of the different models of age estimations by looking at their offsets.

The three non-biostratigraphic age schemes agree well, as seen in Figure 8, when excluding the Brunhes chron (see section 5.1). Figure 9 presents the differences in ages between the various methods of age estimation, paleomagnetically-derived minus marine isotope stage (Mag-MIS) and paleomagnetically-derived minus astrochronologically-derived (Mag-A). If the Brunhes chron is excluded, the Mag-MIS offset is typically larger than Mag-A. This suggests that the astrochronology method is underestimating high sedimentation rates and overestimating low sedimentation rates, if we assume that the MIS ages are near-instantaneous estimates of the sedimentation rate. In intervals where Mag-MIS is smaller than Mag-A, the MIS age seems to be reacting to changes in sedimentation rate more quickly than the astrochronologically-derived ages. Again, this is a weakness of this particular astrochronologic age model, likely due to the large window size, which imparts a 'lag' on the changes in sedimentation rate. A larger window size would mix frequencies over a larger interval, and so react more slowly to changes in sedimentation rate while a smaller window size would react more quickly. Again, the larger window-size was used here to account for the noise in the dataset.

All offsets between the various age models were generally smaller than the time between isotope stages. This suggests that although the above discussion is valid, the paleomagnetically-derived ages are robust, and eliminating the 'tuning' step within the

methods would likely have not changed the MIS-correlations. This also suggests that this is a continuous section, excluding perhaps some portion of the Brunhes chron.

sedimentation rates

The sedimentation rate is calculated in several different forms. First, a linear sedimentation rate was calculated from the paleomagnetic reversal record, both including volcanics and without (Figure 10). The difference between these two, or the volcanic accumulation rate, is in purple. The non-volcanic, or hemipelagic, sedimentation rate curve is different from previous studies. Shipboard chronostratigraphy described a roughly monotonic decrease in sedimentation rate from ~4.5 Ma to present (Expedition 340 Scientists 2013), which is seen in the total sedimentation rate (Figure 10). When the thickness of the volcanically-sourced sediments is removed, the monotonic decrease in rate disappears and the sedimentation rates resemble a step-function. When viewed as a step function, sedimentation rates are ~4 cm/kyr until ~2.2 Ma and ~2 cm/kyr thereafter, partially owing to the increasing thickness of the volcanically-sourced beds from ~3.5-4.5 Ma (purple line, Figure 10), which account for ~1 cm/kyr of the sedimentation rate. Alternatively, there is a gradual decline in sedimentation rate from ~3.5 to ~2.1 Ma, with higher rates before and lower rates after. Either interpretation removes the monotonic increase seen in the sedimentation rate that includes both volcanic and hemipelagic sedimentation.

The sedimentation rate constructed from the marine isotope correlations is much more variable than the paleomagnetically-derived sedimentation rates, but still follows the approximate trends defined by the paleomagnetic rates. The rates are particularly variable prior

to 2 Ma. Rates are ~6 cm/kyr until ~3.65 Ma, then drop to ~4 cm/kyr from ~3.65-2.15 Ma. There is a slow decline in the rates from ~4 cm/kyr to ~2 cm/kyr from ~2.5- ~1.5 Ma. There is a pulse of sediment roughly coincident with the middle Pleistocene Transition (MPT), with rates varying between ~4 and <1 cm/kyr afterwards. Brightness (L*) shows a particularly good agreement with the sedimentation rates. Figure 10 depicts the sedimentation rates, with the black line representing a running mean of L* with a 100 kyr window to remove higher frequency cycles and examine only the longer-term trends. There is a significant correlation between sedimentation rate and L* (See fig. 10 inset, n = 87, Pearson's r = -0.5416 , p value < 0.001). This connection suggests that the lighter sediments (higher L* values) were deposited at a slower rate than the darker sediments (lower L* values). $CaCO_3$% data, from shipboard geochemistry, shows a weak correlation to the L* values throughout the entire record. Although shipboard sampling for $CaCO_3$ measurements attempted to avoid the influence of volcanic sediments and sample purely hemipelagic sedimentation, the distinct possibility that carbonate-free volcanic material, in the form of cryptotephra (dispersed ash), may be influencing the $CaCO_3$% data was suggested by Expedition 340 Geochemistry (Expedition 340 Scientists 2013).

local volcanism / regional effects

There are several possible explanations for the L* to sedimentation rate correlation. First, the additional input of dispersed volcanogenic sediment could strongly affect sedimentation rate. The 3.5-4.5 Ma interval has ~1 cm/kyr observed volcanic sedimentation, whereas the sedimentation is ~4 cm/kyr overall. If we assume, for the sake of discussion, that the flux of purely hemipelagic sediment is constant throughout the entire interval at ~2 cm/kyr (~0-2 Ma

rough average sedimentation rate), there is ~1 cm/kyr of unaccounted for sedimentation in the 3.5-4.5 Ma interval. As the observed volcanically-derived sedimentation is highest throughout this interval, it seems possible that the undetected dispersed ash, or cryptotephra (e.g. McCanta et al. 2015), throughout that interval may also be high. The lower L* value agrees with elevated cryptotephra, as dispersed ash would darken the surrounding sediments. There are pulses of volcanic sediment at ~1.9 Ma which also coincide with inflections in the brightness. This hypothesis, however, does not agree with the land-based local volcanic history. The Silver Hills Volcano on Montserrat was active ~ 2.6 to ~1.2 Ma (Harford et al. 2002), the oldest land-based date for volcanic activity on Montserrat, and the general trend through this interval at Site U1396 is one of increasing brightness and presumably less volcanic ash and other volcaniclastic sediments. Although the volcanogenic sediments could be sourced from elsewhere (e.g., Palmer et al. 2016), and Montserrat is probably older than just the onland ages, it seems likely that these growth phases of subaerial Montserrat (Figure 10) should have a substantial impact on U1396. If a hypothesis of the sedimentation rate changes being purely volcanically-forced is true, then one would expect that the growth of the nearest volcano to have an impact. Rather, the data suggest less volcanic influence, or at least slower sedimentation rates, as Montserrat grows larger.

gateway changes

The closure of the Isthmus of Panama had a profound effect on the oceanography of the Caribbean Sea. In particular, bottom water connection with the Pacific Ocean ceased by ~4.5 Ma (Keigwin 1982; Duque-Caro 1990; Haug and Tiedemann 1998). Other portions of the Central

American Seaway (CAS) history are controversial (for a discussion see Molnar 2008), owing to the prolonged nature of the closure, and/or the possibility that sea level changes derived from glacial-interglacial cycles could have closed and opened the gateway repeatedly (e.g., Groeneveld et al. 2014). There is evidence for greatly reduced oceanographic exchange through the CAS by ~4.2 Ma (e.g., Haug et al. 2001; Jain and Collins 2007), although other authors place 'final closure' later (~3.2-3.6 Ma, Haug and Tiedemann 1998; ~2.4-2.76 Ma, Keller et al. 1989; Kameo and Sato 2000; Groeneveld et al. 2014). Land animal exchange between the continents is observed at 2.7 Ma, offering a strict youngest-limit to the closure history (Webb 1997). At 4.2 Ma there is a substantial drop in productivity recorded by benthic foraminiferal assemblages and $\delta^{13}C$ time series at Site 999 (Jain and Collins 2007). Chaisson (2003) observed a distinct change in menardellid evolution between the Atlantic and Pacific Oceans between 4.5 and 3.0 Ma, with the Caribbean Sea forms occupying higher and more oligotrophic conditions. Both productivity and menardellid evolution are linked the CAS closure, which is thought to displace the locus of productivity and upwelling to the Pacific Ocean while the Caribbean Sea experienced growth of oligotrophic conditions. This expansion of oligotrophic conditions is also seen during the interval of highly variable, or 'pulsed' sedimentation rates at U1396. The hemipelagic sediments at U1396 are largely biogenic so there must be a link between productivity and sedimentation rate. This link is not as simple as higher productivity equals higher sedimentation rate because factors like bottom water corrosiveness, siliceous vs. carbonate productivity, or bottom water current strength (among many others) may also alter the sedimentation rate. The confluence of oligotrophic indicators from Site 999 and pulsed rates at Site U1396 suggest a possible, but counterintuitive, link.

The lower L* values with higher sedimentation rates could suggest that biogenic silica pulses are driving the sedimentation in the lower Pliocene of Site U1396. The sedimentation rate also appears to possibly contain obliquity-forced cycles during the volatile interval. An obvious alternative explanation for the L* values is volcanic sedimentation, but it is difficult to connect obliquity cycles with volcaniclastic sedimentation. Obliquity cycles have been observed in productivity indicators at other locations during the Plio-Pleistocene (e.g., Bolton et al. 2010). The link at Site U1396, however, is highly speculative. The correlations between the $\delta^{18}O$ U1396 data and the MIS LR04 stack is, through the highly variable sedimentation rate interval, based on smaller changes in $\delta^{18}O$ because of the smaller glacial-interglacial changes at those times. The time interval between correlation points is also fairly small, and so minor changes in the points used for correlations could produce substantial impacts on sedimentation rates. The high variability is, however, still seen in the astrochronologically-derived sedimentation rates (not shown). The extreme swings in sedimentation rate also suggest that even if MIS stages were moved by tens of cm the magnitude of the pulses in rate may change, the pulses would remain. The high rates also do not correspond to either extreme glacials or interglacials. Indeed, indicators for high seasonality were observed in the benthic analysis at Site 999 (Jain and Collins 2007) prior to the final closure at ~3.0-2.4 Ma. The pulses in sedimentation may indicate that Site U1396, closer to the equatorial Atlantic Ocean, experienced elevated productivity longer than at the more central Caribbean Sea Site 999, or that a long-term trend toward more oligotrophic conditions was punctuated by intervals of higher productivity.

There are other gateway changes that could have played a role in controlling sedimentation at Site U1396. Mediterranean Outflow Water (MOW) enters the Atlantic Ocean

through the Strait of Gibraltar and is an important component of Atlantic Ocean circulation patterns. Evidence from the Gulf of Cadiz, off the Portugal coast, suggests periods of intensification in MOW strength at 0.7-0.9, 2.0-2.4, and 3.0-3.2 Ma (Hernández-Molina et al. 2014). If this water were to flow into the Caribbean Sea at times, MOW would be the deepest water-mass in the Caribbean Sea due to its high salinity, and thus high density. There is an established glacial-interglacial control on the water entering the Caribbean over the past 200 kyr, with more corrosive Antarctic Intermediate Water (AAIW) during the interglacials and less corrosive glacial North Atlantic Intermediate Water (or upper North Atlantic Deep Water) during the glacials (Haddad and Droxler 1996).

Kaneps (1979) suggested variable Gulf Stream strength throughout the Plio-Pleistocene, interpreting a series of hiatuses on Blake Plateau as intervals of higher Gulf Stream velocity. The precise timing of the hiatuses, however, is suspect as the ages are based on 1970-era biostratigraphic calibrations (hence the 1-myr error bars in Figure 10). If Blake Plateau hiatuses and MOW intensifications were roughly synchronous, then MOW flowing into the Caribbean Sea may have contributed to a strengthened Gulf Stream flow by way of increased salt-driven Atlantic Meridional Overturning Circulation in the North Atlantic (e.g., Ivanovic et al. 2013). At Site U1396 there are intervals of elevated carbonate deposition, very roughly coincident, with the Blake Plateau hiatuses and MOW intensifications. This seems counter to the expectation from the literature (e.g., Haddad and Droxler 1996), as the bottom water bathing Site U1396 would likely be AAIW, a nutrient rich but corrosive water mass. MOW, on the other hand, would be less corrosive, nutrient poor, and warm. The lithostratigraphy from Site U1396 agrees with different water masses bathing the site throughout the Pleistocene. At ~600 ka and again at

~400 ka there are calcareous sand intervals, which are associated with lower sedimentation rate suggesting extensive winnowing removing the fine fraction (discussed in Wall-Palmer et al. 2014). Removing fine sediment would lower the sedimentation rate. These sandy intervals appear to be associated with MIS 15-16 and MIS 10-12. Directly preceding these sandy intervals, the interval from 0.55 to 0.75 Ma is one of low $\delta^{18}O$ variability in the benthic record. A change in Caribbean Sea bottom water may explain the decreased benthic $\delta^{18}O$ variability, if it were episodic, only bathing benthic organisms in warm water during glacials, and a relatively cooler water mass during interglacials. This would have the effect of flattening the curve, effectively removing the benthic glacial-interglacial differences in $\delta^{18}O$ while retaining the observed high planktic $\delta^{18}O$. While the dates for MOW intensification do not agree with the lower variability in benthic $\delta^{18}O$, MOW dates are at present poorly constrained (Hernández-Molina et al. 2014). Currently MOW intensification occurs at ~0.7-0.9 Ma (Hernández-Molina et al. 2014). Our low $\delta^{18}O$ variance interval is ~150 kyr younger, with low sedimentation rate and winnowing occurring at ~0.7-0.6 Ma and ~0.5-0.35 Ma, but the mismatch could simply be due to poorly constrained dates from the MOW outflow studies. It should be noted that geochemical evidence points to limited MOW influence in the Caribbean during the Plio-Pleistocene (Osborne et al. 2014), that evidence is only from after 2 Ma, well after the hypothesis described above. The above hypothesis is speculative, but remains a possible explanation for a number of different observations that cannot simply be due to volcaniclastic influence at Site U1396.

A second pulse of winnowing coincides with MIS 11. However, low benthic $\delta^{18}O$ variability through this interval is likely due to a limited number of $\delta^{18}O$ values, as the sample resolution shrinks to ~50 kyr. While there is similarity between the winnowing pulse at MIS 15

and MIS 11, we cannot rule out a data density issue at MIS 11. The planktic record suggests that while MIS 15 benthic variability is limited, MIS 10 and MIS 12 may be missing in a hiatus, as the typical glacial $\delta^{18}O$ values are missing from both benthic and planktic records.

Perhaps a more likely connection between gateway changes and rates of sedimentation is thermohaline circulation. Haug and Tiedemann (1998) demonstrated a link between the salinity contrast, formed by CAS closure, between Pacific and Atlantic Ocean. This contrast, with saltier Atlantic Ocean water, helps to boost formation of North Atlantic Deep Water (NADW), which in turn boosts thermohaline circulation. Several studies have demonstrated this link (e.g., Zhang et al. 2012; Osborne et al. 2014) both in proxy reconstruction and inter-model comparison. Proxy reconstructions, especially the geochemical reconstructions both from oxygen isotope gradients between Pacific and Atlantic basins and other methods (e.g., Osborne et al. 2014), suggest that this was not a simple single increase, that in fact there were multiple fluctuations in the strength superimposed on the long-term trend of increased thermohaline circulation. These fluctuations in thermohaline circulation were of varying duration, but had ~100-kyr scale durations, and so could be some of the variability that is seen in the sedimentation rates at Site U1396, while the longer term trend in faster bottom water flow would explain the general trend to slower sedimentation rates at U1396 within the upper portion of the record.

Increased bottom water current flow due to increased thermohaline circulation, and therefore increased winnowing, is supported by the qualitative core description. There is a change at Site U1396 to more calcareous sand sedimentation within the upper portion of the record, away from the lower, more ooze-dominated sedimentation of the lower portion. This

can be seen most clearly on the CCSF-NV lithologic section on Figure 2. This mean increase in grain size, likely due to winnowing of the fine-grained material, would decrease the sedimentation rate. In fact, as seen in Figure 7, ooze deposition is coincident with increased sedimentation rate during the Brunhes chron, though this depends on the age model.

Realistically, the observed changes in sedimentation rate and brightness are a mixture of different factors: volcanic input, carbonate and siliceous productivity, and thermohaline circulation. The period from ~3-4 Ma could have been a period of highly variable productivity, driven by obliquity and incomplete construction of the CAS. Thermohaline circulation, as the CAS had not completely closed, could also have been uneven, and sped up and slowed down in fits, as seen in Osborne et al. (2014), leading to the highly volatile rates observed through that interval. As CAS closure became more complete after 3 Ma, the increase in thermohaline circulation drove faster bottom water circulation over Site U1396, leading to increased winnowing and lower sedimentation rates, resulting in the gradual decline in rates observed. Lastly, the low sedimentation rates, with pulses of winnowing, could have been due to the lower productivity and increased thermohaline circulation and thus variation in bottom water character during the 0-2 Ma interval. Throughout the entire section, there must be a substantial fraction of the sedimentation rate controlled by volcaniclastic sediment. The volcanic influence here is only constrained somewhat within this study, further work must be done to detail the degree to which there is dispersed ash within the sediments at Site U1396. This analysis provides the first step to understanding the other, non-volcanic, factors contributing the accumulation of sediment at this location.

CONCLUSIONS

1. Site U1396, drilled ~33 km southwest of Montserrat, contains a relatively continuous sequence of Pliocene and Pleistocene sedimentation. There is a general trend to decreasing sedimentation rate towards the present, both in volcanic and non-volcanic sedimentation.

2. The chronostratigraphy of Site U1396 is based on planktic foraminifer biostratigraphy, calcareous nannofossil biostratigraphy, magnetostratigraphy, astrochronology, and oxygen isotope chemostratigraphy (marine isotope stages). The resulting chronostratigraphy provides a detailed framework to reconstruct the paleoceanography and record of sediment accumulation in the northeastern Caribbean.

3. A revision of the previous Wall-Palmer et al. (2014) chronostratigraphy is proposed. Here we highlight differences observed in the chonostratigraphic schemes employed at U1396 and use the longer perspective of U1396 to develop an alternative hypothesis, which fits better when considering the Brunhes chron as a whole. Although there is a call for further chronostratigraphic investigations, these findings may have dramatic implications for the reconstruction of the volcanic history of Montserrat.

4. Two biostratigraphic datums used extensively shipboard (B *Globigerinella calida* and T *Globorotalia flexuosa*) were found to be unreliable at Site U1396. Use of those datums at other Exp. 340 sites should be restricted to occurrences supported by additional chronostratigraphic

information (calcareous nannofossils, for example).

5. There is a strong correlation ($p < 0.001$) between sedimentation rate and L* (brightness). There is weak correlation between ($p < 0.1$) brightness and $CaCO_3$ content throughout the entire record, but some intervals of L* qualitatively appear to be controlled by carbonate content. This suggests that the main phases of Montserrat volcanism may not be contributing strongly to the sedimentation at Site U1396, as the growth of Montserrat (<2.6 Ma) occurs during times of lower sedimentation rates at Site U1396.

6. Sedimentation rate at Site U1396 (IODP Expedition 340) is likely controlled by a mix of factors, including volcanogenic, lithogenic, and biogenic sediment sources. A series of hypotheses to explain the rates were explored, with connections to Site 999, a more centrally located Caribbean Sea ODP Site, with suggestions for future work to elucidate the direct causes. Highly variable, but consistently elevated, rates of sedimentation are surprisingly high during a period normally considered to be oligotrophic within the Caribbean Sea. It is suggested, therefore, that a more likely cause is due to bottom water conditions, including episodic changes in bottom water flow rates in the Pliocene and increased winnowing into the Pleistocene, associated with CAS closure through the studied interval.

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References

ALJAHDALI, M.H., 2013. Pliocene-Pleistocene Calcareous Nannofossil Biostratigraphy of Iodp Hole 1396c Adjacent To Montserrat Island In The Lesser Antilles, Caribbean Sea, Plus Experimentally Induced Diagnesis. *Electronic Theses, Treatises and Dissertations*. Paper 7270.

BACKMAN, J., RAFFI, I., RIO, D., FORNACIARI, E., and PÄLIKE, H., 2012. Biozonation and biochronology of Miocene through Pleistocene calcareous nannofossils from low and middle latitudes. *Newsletters on Stratigraphy*, 45:221-244.

BÉ, A.W.H., and TOLDERLUND, D.S., 1971. Distribution and ecology of living planktonic foraminifera in surface waters of the Atlantic and Indian Ocean. In: FUNNEL, B.M., RIEDEL, W.R. Eds., *The Micropaleontology of Oceans*, 105-149. Cambridge: Cambridge University Press.

BECKER, R.A., WILKS, A.R. (Original S code), R. BROWNRIGG (R version), T. P. MINKA (Enhancements), 2015. maps: Draw Geographical Maps. *R package* version 2.3-11. http://CRAN.R-project.org/package=maps.

BERGGREN, W.A., HILGEN, F.J., LANGEREIS, C.G., KENT, D.V., OBRADOVICH, J.D., RAFFI, I., RAYMO, M.E., SHACKLETON, N.J., 1995. Late Neogene chronology: new perspectives in high-resolution stratigraphy. *Geological Society of America Bulletin*, 107:1272-1287.

BOLTON, C.T., GIBBS, S.J., and WILSON, P.A., 2010. Evolution of nutricline dynamics in the equatorial Pacific during the late Pliocene. *Paleoceanography,* 25:PA1207. doi:10.1029/2009PA001821

CANDE, S.C. and KENT, D.V., 1995. Revised calibration of the geomagnetic polarity timescale for the Late Cretaceous and Cenozoic. *Journal of Geophysical Research,* 100:6093-6095.

CAREY, S.N. and SCHNEIDER, J-L., 2001. Volcaniclastic processes and deposits in the Deep-Sea. *Developments in Sedimentology,* 63:457-515.

CASSIDY, M., TROFIMOVS, J., PALMER, M.R., TALLING, P.J., WATT, S.F.L. MORETON, S.G., and TAYLOR, R.N. 2013. Timing and emplacement dynamics of newly recognised mass flow deposit at ~8-12 ka offshore Soufriere Hills volcano, Montserrat: How submarine stratigraphy can complement subaerial eruption histories. *Journal of Volcanology and Geothermal Research,* 253:1-14.

CASSIDY, M., WATT., S.F.L, PALMER, M.R., TROFIMOVS, J., SYMONS, W., MACLACHLAN, S.E., and STINTON, A.J., 2014. Construction of volcanic records from marine sediment cores: A review and case study (Montserrat, West Indies). *Earth-Science Reviews*, 138:137-155.

CHAISSON, W.P., 2003. Vicarious living: Pliocene menardellids between an isthmus and an ice sheet. *Geology* 31(12): 1085-1088.

CHAISSON, W.P. and D'HONDT, S.L., 1999. Neogene planktonic foraminifer biostratigraphy at Site 999, western Caribbean Sea. In: LECKIE, R.M., SIGURDSSON, H., ACTON, G.D., and

DRAPER, G., Eds., *Proceedings of the Ocean Drilling Program, Scientific Results*, *165*, 19-56. College Station: Ocean Drilling Program.

CHAISSON, W.P. and LECKIE, R.M., 1993. High-resolution Neogene planktonic foraminifer biostratigraphy of Site 806, Ontong Java Plateau (western Equatorial Pacific). In: BERGER, W.H., KROENKE, L.W., and MAYER, L.A., Eds., *Proceedings of the Ocean Drilling Program, Scientific Results*, *130*, 137-178. College Station: Ocean Drilling Program.

CHAISSON, W.P. and PEARSON, P.N., 1997. Planktonic foraminifer biostratigraphy at Site 925: Middle Miocene-Pleistocene. In: SHACKLETON, N.J., CURRY, W.B., and BRALOWER, T.J., Eds., *Proceedings of the Ocean Drilling Program, Scientific Results*, *154*, 3-31. College Station: Ocean Drilling Program.

CHAPRONIERE, G.C.H., STYZEN, M.J., SAGER, W.W., NISHI, H., QUINTERNO, P.J., and ABRAHAMSEN, N., 1994. Late Neogene biostratigraphic and magnetostratigraphic synthesis, Leg 135. In: HAWKINS, J., PARSON, L. ALLAN, J. et al. Eds., *Proceedings of the Ocean Drilling Program, Scientific Results*, *135*, 857-887. College Station: Ocean Drilling Program.

CLARK, P. U., ARCHER, D., POLLARD, D., BLUM, J. D., RIAL, J. A., BROVKIN, V., MIX, A. C., PISIAS, N. G., and ROY, M., 2006. The middle Pleistocene transition: Characteristics, mechanisms, and implications for long-term changes in atmospheric pCO_2. *Quaternary Science Reviews,* 25: 3150-3184.

COUSSENS, M.F., WALL-PALMER, D., TALLING, P.J., WATT, S.F.L, HATTER, S.J., CASSIDY, M., CLARE, M., JUTZELER, M., HATFIELD, R., MCCANTA, M., KATAOKA, K.S., ENDO, D., PALMER, M.R., STINTON, A., FUJINAWA, A., BOUDON, G., LE FRIANT, A.,

ISHIZUKA, O., GERNON, T., ADACHI, T., ALJAHDALI, M., BREITKREUZ, C., FRAASS, A.J., HORNBACH, M.J., LEBAS, E., LAFUERZA, S., MAENO, F., MANGA, M., MARTINEZ-COLON, M., MCMANUS, J., MORGAN, S., SAITO, T., SLAGLE, A., SUBRAMANYAM, K.S.V., TAMURA, Y., TROFIMOVS, J., VILLEMANT, B., WANG, F., and EXPEDITION 340 SCIENTISTS, 2016. Synthesis: stratigraphy and age control for IODP Sites U1394, U1395, and U1396 offshore Montserrat in the Lesser Antilles. In: LE FRIANT, A., ISHIZUKA, O., STRONCIK, N.A., and EXPEDITION 340 SCIENTISTS, *Proceedings of the Integrated Ocean Drilling Program*, 340. Tokyo: Integrated Ocean Drilling Program Management International, Inc.. doi:10.2204/iodp.proc.340.204.2016

CRUTCHLEY, G.J., KARSTENS, J., BERNDT, C., TALLING, P.J., WATT, S.F.L. VARDY, M.E., HÜHNERBACH, V., URLAUB, M., SARKAR, S., KLAESCHEN, D., PAULATTO, M., LE FRIANT, A., LEBAS, E., and MAENO, F., 2013. Insights into the emplacement dynamics of volcanic landslides from high-resolution 3D seismic data acquired offshore Montserrat, Lesser Antilles. *Marine Geology,* 335:1-15.

DUQUE-CARO, H., 1990. Neogene stratigraphy, paleoceanography, and paleobiogeography in northwest South America and the evolution of the Panama Seaway. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 77:203-234.

ERICSON, D.B. and WOLLIN, G., 1968. Pleistocene climates and chronology in deep-sea sediments. *Science,* 162:1227-1234.

EXPEDITION 340 SCIENTISTS, 2013. Site U1396, in: LE FRIANT, A., ISHIZUKA, O., STRONCIK, N.A., and EXPEDITION 340 SCIENTISTS, *Proceedings of the Integrated Ocean Drilling Program*, *340*. Tokyo: Integrated Ocean Drilling Program Management International,

Inc.. doi:10.2204/iodp.proc.340.106.2013

GROENEVELD, J., HATHORNE, E.C., STEINKE, S., DEBEY, H., MACKENSEN, A., and TIEDEMANN, R., 2014. Glacial induced closure of the Panamanian Gateway during Marine Isotope Stages (MIS) 95-100 (~2.5 Ma). *Earth and Planetary Science Letters,* 404:296-306.

HADDAD, G.A. and DROXLER, A.W., 1996. Metastable CaCO3 dissolution at intermediate water depths of the Caribbean and western North Atlantic: Implication for intermediate water circulation during the past 200,000 years. *Paleoceanography,* 11:701-716.

HARFORD, C.L., 2002. The volcanic evolution of Montserrat using 40Ar/39Ar geochronology. In: DRUITT, T.H., KOKELAAR, B.P., Eds., *Geological Society Memoir No. 21: The Eruption of Soufrière Hills Volcano, Montserrat, from 1995 to 1999*, 93-113. London: Geological Society of London.

HATFIELD, R.G., 2015. Data report: stratigraphic correlation of Site U1396 and creation of a composite depth scale and splice. In: LE FRIANT, A., ISHIZUKA, O., STRONCIK, N.A., and EXPEDITION 340 SCIENTISTS, Eds., *Proceedings of the Integrated Ocean Drilling Program*, *340*. Tokyo: Integrated Ocean Drilling Program Management International, Inc. **http://dx.doi.org/10.2204/iodp.proc.340.202.2015**.

HAUG, G.H. and TIEDEMANN, R., 1998. Effect of the formation of the Isthmus of Panama on Atlantic Ocean thermohaline circulation. *Nature,* 393:673-676.

HAUG, G.H., TIEDEMANN, R., ZAHN, R., and RAVELO, A.C., 2001. Role of Panama uplift on oceanic freshwater balance. *Geology,* 29:207-210.

HERD, R.A., EDMONDS, M., and BASS, V.A., 2005. Catastrophic lava dome failure at Soufriere Hills Volcano, Montserrat, 12-13 July 2003. *Journal of Volcanology and Geothermal Research,* 148:234-252. doi: 10.1016/j.jvolgeores.2005.05.003

HERNÁNDEZ-MOLINA, F.J., STOW, D.A., ALVAREZ-ZARIKIAN, C.A., ACTON, G., BAHR, A., BALESTRA, B., DUCASSOU, E., FLOOD, R., FLORES, J.-A., FUROTA, S., GRUNERT, P., HODELL, D., JIMENEZ-ESPEJO, F., KIM, J.K., KRISSEK, L. KURODA, J., LI, B., LLAVE, E., LOFI, J., LOURENS, L. MILLER, M., NANAYAMA, F., NISHIDA, N., RICHTER, C., ROQUE, C., PEREIRA, H., GOÑI, M.F.S., SIERRO, F.J., SINGH, A.D., SLOSS, C., TAKASHIMIZU, Y., TZANOVA, A., VOELKER, A., WILLIAMS, T., and XUAN, C., 2014. Onset of Mediterranean outflow into the North Atlantic. *Science,* 344:1244-1250.

IVANOVIC, R.F., VALDES, P.J., FLECKER, R., GREGOIRE, L.J., and GUTJAHR, M., 2013. The parameterization of Mediterranean-Atlantic water exchange in the Hadley Centre model HadCM3, and its effect on modelled North Atlantic climate. *Ocean Modelling,* 62:11-16.

JUTZELER, M., WHITE, J.D.L. TALLING, P.J., MCCANTA, M., MORGAN, S., LE FRIANT, A., and ISHIZUKA, O., 2014. Coring disturbances in IODP piston cores with implications for offshore record of volcanic events and the Missoula megafloods. *Geochemistry, Geophysics, Geosystems*, 15:3572–3590, doi:10.1002/2014GC005447.

JUTZELER, M., TALLING, P.J., WHITE, J.D.L. and EXPEDITION 340 SCIENTISTS, 2016. Data report: coring disturbances in IODP Expedition 340, a detailed list of intervals with fall-in and flow-in. In: LE FRIANT, A., ISHIZUKA, O., STRONCIK, N.A., and EXPEDITION 340 SCIENTISTS, *Proceedings of the Integrated Ocean Drilling Program*, 340. Tokyo: Integrated

Ocean Drilling Program Management International, Inc.. doi:10.2204/iodp.proc.340.206.2016

KAMEO, K. and SATO, T., 2000. Biogeography of Neogene calcareous nannofossils in the Caribbean and the eastern equatorial Pacific – floral response to the emergence of the Isthmus of Panama. *Marine Micropaleontology*, 39:201-218.

KANEPS, A.G., 1979. Gulf Stream: Velocity fluctuations during the Late Cenozoic. *Science,* 204:297-301.

KEIGWIN, L., 1982. Isotopic paleoceanography of the Caribbean and East Pacific: Role of Panama uplift in late Neogene time. *Science,* 217:350-353.

KELLER, G., ZENKER, C.E., and STONE, S.M., 1989. Late Neogene history of the Pacific-Caribbean gateway. *Journal of South American Earth Sciences*, 2:73-108.

KENNETT, J.P. and HUDDLESTUN, P., 1972. Late Pleistocene paleoclimatology, foraminiferal biostratigraphy and tephrochronology, western Gulf of Mexico. *Quaternary Research,* 2:38-69.

LE FRIANT, A., DEPLUS, C., BOUDON, G., FEUILLET, N., TROFIMOVS, J., KOMOROWSKI, J.-C., SPARKS, R.S.J., TALLING, P., LOUGHLIN, S., PALMER, M., and RYAN, G., 2010. Eruption of Soufriere Hills (1995-2009) from an offshore perspective: Insights from repeated swath bathymetry surveys. *Geophysical Research Letters,* 37.

LE FRIANT, A., LOCK, E.J., HART, M.B., BOUDON, G., SPARKS, R.S.J., LENG, M.J., SMART, C.W., KOMOROWSKI, J.C., DEPLUS, C., and FISHER J.K., 2008. Late Pleistocene tephrochronology of marine sediments adjacent to Montserrat, Lesser Antilles volcanic arc. *Journal of the Geological Society,* 165:279-289.

LISIECKI, L.E. and RAYMO, M.E., 2005. A Pliocene-Pleistocene stack of 57 globally distributed benthic $\delta^{18}O$ records. *Paleoceanography,* 20:PA1003. doi:10.1029/2004PA001071.

LOURENS, L.J., HILGEN, F.J., SHACKLETON, N.J., LASKAR, J., and WILSON, D., 2004. The Neogene Period. In: GRADSTEIN, F.M., OGG, J.G., and SMITH, A.G., Eds., *Geological Time Scale 2004*, 409-440. Cambridge: Cambridge University Press.

MACDONALD, R., HAWKESWORTH, C.J., and HEATH, E., 2000. The Lesser Antilles volcanic chain: a study in arc magmatism. *Earth Science Reviews,* 49:1-76.

MARTINSON, D.G., PISIAS, N.G., HAYS, J.D., IMBRIE, J., MOORE JR., T.C., and SHACKLETON, N. J., 1987. Age dating and the orbital theory of the iceages: Development of a high-resolution 0 to 300,000-year chronostratigraphy. *Quaternary Research,* 27:1–29. doi:10.1016/0033-5894(87)90046-9

MCCANTA, M.C., HATFIELD, R.G., THOMAS, B.J., HOOK, S.J., and FISHER, E., 2015. Identifying cryptotephra units using correlated rapid, nondestructive methods: VSWIR spectroscopy, X-ray fluorescence, and magnetic susceptibility. *Geochemistry Geophysics Geosystems,* 16:4029-4056. doi:10.1002/2015GC005913.

MEYERS, S.R., 2014. astrochron: An R Package for Astrochronology. http://cran.r-project.org/package=astrochron

MEYERS, S.R. and SAGEMAN, B.B., 2004. Detection, quantification, and significance of hiatuses in pelagic and hemipelagic strata. *Earth and Planetary Science Letters,* 224:55-72.

MIX, A.C., LE, J., SHACKLETON, N.J., 1995. Benthic foraminiferal stable isotope stratigraphy of Site 846: 0-1.8 Ma. In: PISIAS, N.G., MAYER, L.A., JANECEK, T.R., PALMER-JULSON, A.,

VAN ANDEL, T.H., Eds., *Proceedings of the Ocean Drilling Program: Scientific Results, 138*, 839-854.

MOLNAR, P., 2008. Closing of the Central American Seaway and the Ice Age: A critical review. *Paleoceanography,* 23:PA2201.

OGG, J.G., 2012. The Geomagnetic Polarity Timescale. In: GRADSTEIN, F.M., OGG, J.G., and SCHMITZ, M.D., OGG, G.M, Eds., *The Geologic Time Scale 2012*, 85-113. Amsterdam: Elsevier.

OSBORNE, A.H., NEWKIRK, D.R., GROENVELD, J., MARTIN, E.E., TIEDEMANN, R., and FRANK, M., 2014. The seawater neodymium and lead isotope record of the final stages of Central American Seaway closure. *Paleoceanography,* 29:715-729. doi:10.1002/2014PA002676.

PÄLIKE, H., NORRIS, R.D., HERRLE, J.O., WILSON, P.A., COXALL, H.K., LEAR, C.H., SHACKLETON, N.J., TRIPATI, A.K., and WADE, B.S., 2006. The heartbeat of the Oligocene climate system. *Science,* 314:1894-1898.

PALMER, M.R., HATTER, S.J., GERNON, T.M., TAYLOR, R.N., CASSIDY, M., JOHNSON, P., LE FRIANT, A., and ISHIZUKA, O., 2016. Discovery of a large 2.4 Ma Plinian eruption of Basse-Terre, Guadeloupe, from the marine sediment record. *Geology,* G37193.1. doi:10.1130/G37193.1.

PARKER, F.L., 1962. Planktonic foraminiferal species in Pacific Sediments. *Micropaleontology*, 8(2):219-254.

PEARSON, P.N., 1995. Planktonic foraminifer biostratigraphy and the development of pelagic caps on guyots in the Marshall Islands Group. In: HAGGERTY, J.A., PREMOLI SILVA, I.,

RACK, R., and MCNUTT, M.K., Eds., *Proceedings of the Ocean Drilling Program, Scientific Results, 144*, 21-59.

R CORE TEAM, 2014. R: A language and environment for statistical computing. *R Foundation for Statistical Computing*, Vienna, Austria. URL http://www.R-project.org/.

REID, R.P., CAREY, S.N., and ROSS, D.R., 1996. Late Quaternary sedimentation in the Lesser Antilles island arc. *GSA Bulletin,* 108:78-100.

ROBINSON, M.M., BARTOL, M., BOLTON, C.T., DING, X., GARIBOLDI, K., ROMERO, O.E., and THE EXPEDITION 353 SCIENTISTS, 2016. Biostratigraphic summary. In: CLEMENS, S.C., KUHNT, W., LEVAY, L.J., and THE EXPEDITION 353 SCIENTISTS, Eds., *Proceedings of the International Ocean Discovery Program*, *353*, Tokyo: Integrated Ocean Drilling Program Management International, Inc. http://dx.doi.org/10.14379/iodp.proc.353.109.2016.

SPEZZAFERRI, S., KUCERA, M., PEARSON, P.N., WADE, B.S., RAPPO, S., POOLE, C.R., MORARD, R., and STALDER, C., 2015. Fossil and genetic evidence for the polyphyletic nature of the planktonic foraminifera "*Globigerinoides*", and description of the new genus *Trilobatus*. *PLoS ONE,* 10(5): e0128108. doi:10.1371/journal.pone.0128108

THIERSTEIN, H.R., GEITZENAUER, K.R., MOLFINO, B., and SHACKLETON, N.J., 1977. Global synchroneity of late Quaternary coccolith datum levels: Validation by oxygen isotopes. *Geology,* 5:400-404.

TROFIMOVS, J., FISHER, J.K., MACDONALD, H.A., TALLING, P.J., SPARKS, R.S.J., HART, M.B., SMART, C.W., BOUDON, G., DEPLUS, C., and KOMOROWSKI, J.C., 2010. Evidence for carbonate platform failure during rapid sea-level rise; ca 14,000 year old bioplastic flow deposits in the Lesser Antilles. *Sedimentology,* 57:735-759.

WADE, B.S., PEARSON P.N., BERGGREN W.A., and PÄLIKE, H., 2011. Review and revision of Cenozoic tropical planktonic foraminiferal biostratigraphy and calibration to the geomagnetic polarity and astronomical time scale. *Earth-Science Reviews,* 104:111-142.

WALL-PALMER, D., COUSSENS, M., TALLING, P. J., JUTZELER, M., CASSIDY, M., MARCHANT, I., PALMER, M. R., WATT, S. F. L. SMART, C. W., FISHER, J. K., HART, M. B., FRAASS, A. J., TROFIMOVS, J., LE FRIANT, A., ISHIZUKA, O., ADACHI, T., ALJAHDALI, M., BOUDON, G., BREITKREUZ, C., ENDO, D., FUJINAWA, A., HATFIELD, R., HORNBACH, M. J., KATAOKA, K., LAFUERZA, S., MAENO, F., MANGA, M., MARTINEZ-COLON, M., MCCANTA, M., MORGAN, S., SAITO, T., SLAGLE, A. L. STINTO, A. J., SUBRAMANYAM, K. S. V., TAMURA, Y., VILLEMANT, B., and WANG, F., 2014. Late Pleistocene stratigraphy of IODP Site U1396 and compiled chronology offshore of south and southwest Montserrat, Lesser Antilles. *Geochemistry, Geophysics, Geosystems,* 15. doi: 10.1002/2014GC005402.

WEAVER, P.P.E. and CLEMENT, B.M., 1986. Synchroneity of Pliocene planktonic foraminiferal datums in the North Atlantic. *Marine Micropaleontology,* 10:295-307.

WEBB, S.D. 1997. The great American faunal interchange. In: COATES, A.G., Ed., *Central America: A natural and cultural history*, 97-122. New Haven: Yale University Press.

ZHANG, X., PRANGE, M., STEPH, S., BUTZIN, M., KREBS, U., LUNT, D.J., NISANCIOGLU, K.H., PARK, W., SCHMITTNER, A., SCHNEIDER, B., and SHULZ, M., 2012. Changes in equatorial Pacific thermocline depth in response to Panamanian seaway closer: Insights from a multi-model study. *Earth and Planetary Science Letters,* 317-318:76-84.

Figure Captions

Figure 1. Site Map. Map showing surface currents (black), as well as entry points for bottom waters (grey) to the Caribbean Sea. ODP Site 999 and IODP Site U1396 are highlighted as well. Base map from R-package 'maps' (Becker et al. 2015).

Figure 2. Stratigraphic data transformation process. First panel depicts major lithology for each hole (A, B, C) with Color Reflectance Brightness (L*) for each hole (A is red, B green, and C blue). Key to the colors for the major lithology is shown on the far right. Depths for this panel are all on CCSF-A.

Second panel depicts the spliced stratigraphy on the CCSF-A depth scale, with each hole as a distinct column. L* in this panel only includes data included from the splice.

Third panel depicts the composite section on the CCSF-D depth scale, with volcanic units and hemipelagic/pelagic sediments in distinct columns. L* in this panel is the spliced L* sequence.

Fourth panel depicts the composite section removing all sediments with a volcanic major lithology. Both lithostratigraphic column and L* in this panel are not depicted as true depth, but are depicted on the CCSF-NV non-volcanic depth scale (See text).

Figure 3. Results of 0-1 Ma Evolutive Harmonic Analysis (EHA). Left-most panel is the L* brightness record, with volcanic sediments removed (CCSF-NV) and put on a paleomagnetic timescale. Second panel is the spectral power (hotter colors denote higher power). Third panel is amplitude of spectra (hotter colors denote larger amplitude at depicted frequency). Final

panel is the results of the harmonic F-test, depicting where there is significant spectral power. The results of the harmonic F-test were used to tune. The horizontal black line on the final panel depicts a paleomagnetic sedimentation rate control point. White lines above and below depict the earliest that the EHA 'feels' the abrupt sedimentation rate change which occurs at the paleomagnetic datum. Note the 'smearing' about that point seen in the changing frequencies throughout the highlighted interval. Grey lines depict expected orbital frequencies (e eccentricity, o obliquity, p procession) if the sedimentation rate were constant. The green line depicts the frequency described by a 100-kyr period.

Figure 4. Summary of transformations from depth (CCSF-D) to Marine Isotope Ages for $\delta^{18}O$ record. A is spliced core description lithostratigraphy, on the CCSF-D depth scale. Paleomagnetic stripe (B) is from Hatfield (2015; CCSF-D). Planktic foraminiferal biozonation (C) is from this study, CCSF-D. D separates the individual species $\delta^{18}O$ values (red is *Cibicidoides robertsonianus*, brown is *Cibicidoides mundulus*, black is *Planularia wuellerstofi*, orange is mixed) and plots them on the CCSF-D depth scale. PMag Age (E) is the species $\delta^{18}O$ records with ages as defined by a linear sedimentation rate from only paleomagnetic datums. Composite (F) is the composite $\delta^{18}O$ record on the Pmag Age scale (see 3. Methods). The light grey polygon behind the $\delta^{18}O$ values is the error associated with the $\delta^{18}O$ measurements (0.1‰ for P. *wuellerstofi,* and 0.14‰ for other species, see 3. Methods). Astro Age (G) employs the astrochonology generated in this study for ages. LR04 Stack (H) is from Liesecki & Raymo (2005). MIS Age (I) is the isotopic data with a chronostratigraphy resulting from the correlations between the composite record (Astro Age, G) to the LR04 benthic stack (H). The LR04 stack then provides the

numerical ages for the final age model (I). Individual grey lines of correlation cannot be traced across the entire figure, instead they were chosen to elucidate the individual transformations they connect. Lines from Astro Age (G) to LR04 Stack (H) to MIS Age (I) are continuous, however. Paleomagnetic stripe in J uses ages from Ogg et al. (2012). Within K, the first lithostratigraphic column is the hypothetical 'no volcanics' lithostratigraphic column (CCSF-NV) with age, while the second column is the true lithostratigraphic column with age. All colors follow Figure 2. All $\delta^{18}O$ scales are the same width.

Figure 5. Histogram of $\delta^{18}O$ offsets between benthic species. A depicts the offset between *Cibicidoides robertsonianus* and *Planulina wuellerstorfi.* Large black line depicts the combined machine errors for two measurements. Red line depicts the mean for the values within the histogram. Because there were only two samples with both species, the green line depicts the expected offset between *C. robertsonianus* to *P. wuellerstorfi* using *Cibicidoides mundulus* as an intermediary. B depicts the offset between *Cibicidoides mundulus* and *Planulina wuellerstorfi.* Large black line depicts the combined machine errors for two measurements. Red line depicts the mean for the values within the histogram. C depicts the offset between *Cibicidoides robertsonianus* and *Cibicidoides mundulus.* Large black line depicts the combined machine errors for two measurements. Red line depicts the mean for the values within the histogram.

Table 1. Table of planktic foraminifera biostratigraphic datums. Bolded lines denote datums used as primary zonal marker, unbolded lines denote secondary datums. Age columns are from Wade et al. (2011). a denotes an age calibrated to the Cande and Kent (1995) time scale, while b

denotes calibration to the Lourens et al. (2004) astrochronological timescale. Sample is the highest or lowest sample in which the species was found. Sample Depths CSF-B uses the midpoint of the sample depths, and the shipboard composite depth scale. T [CCSF-D] and B [CCSF-D] is the possible range in depths for each datum. T PMag and B PMag is the range in age for each datum, derived from the linear paleomagnetic ages. T Astro and B Astro is the range in age for each datum, derived from the astrochronological tuning. T MIS and B MIS is the range in age for each datum, derived from the correlation to the LR04 benthic $\delta^{18}O$. Offset is the difference between the midpoint MIS age and the astrochronologically-tuned calibrated age (Wade et al. 2011). * denotes ages presented in Wall-Palmer et al. (2014). *Globorotalia flexuosa* was found in the first sample, while *Globorotalia crassaformis* s.l. was found in the last sample, and so neither datum has a true top or bottom, respectively.

Figure 6. Summary of differences between Wade et al. (2011) age datums and findings at Site U1396 with important Scanning Electron Micrographs (SEM). Ages for the biostratigraphic datums are presented as MIS ages, with the horizontal line corresponding to the chronostratigraphic position of the top or bottom. Primary datums are bolded. Colored datums correspond to the SEMs at the sides of the figure. Imaged foraminifera are either from the sample in which the datum was recorded (e.g., *Globorotalia pertenuis*) or nearby core catcher samples. Core catchers are not the precise base/top, as CC samples were not included in the splice. They are as close as was possible, however. All scale bars are 100 µm. *Globorotalia tumida, G. flexuosa* (aberrant form), and *G. flexuosa* are from Sample 340-U1396C-3H, CC. *Globorotalia*

pertenuis is from Sample 340-U1396C-6H-3, 112-114 cm. *Dentoglobigerina altispira* is from Sample 340-U1396C-8H, CC.

Figure 7. Summary of the two contrasting interpretations for the Brunhes chron chronostratigraphy. Left panel depicts the Wall-Palmer et al. (2014) interpretation, with revised correlations only from MIS 15 to the base of the figure. Inset grey box is CARMON-2 stratigraphy (Le Friant et al. 2008). Right panel depicts the proposed revision to the chronostratigraphy. %*Globorotalia menardii-tumida* zonation scheme (orange) is depicted as correlated to the marine isotope stages by Reid et al. (1996), which ends within zone T (approx. MIS 19). Black polygon is the % *G. menardii-tumida* from Wall-Palmer et al. (2014), while grey is the newly-generated data from this study (points denote samples counted). LR04 Stack (grey) is from Liseicki and Raymo (2005), planktic foraminiferal oxygen isotope stack (purple) is from Martinson et al. (1987). The B *Emiliana huxleyi* datum within the left panel is the datum employed in Wall-Palmer et al. (2014), with the calibrated ages from Ogg et al. (2012), while the blue line (right panel only) refers to the other B *E. huxleyi* (Aljahdali; unpublished Masters Thesis). Green line is the *G. ruber* oxygen isotope record from Wall-Palmer et al. (2014), with new data beginning at approximately MIS 8 on the left panel, and MIS 13 on the right panel. Black rectangles are the paleomagnetic chron interpretation from Hatfield (2015). Sedimentation rates are calculated as m/myr. Stratigraphic columns follow figure 2. Slight offset in event bed from Wall-Palmer et al. (2014) and the lithostratigraphy presented here is due to the calculation of sediment ages and slight misfit in the correlated ages in this study. The event bed is the same as topmost volcanic unit.

Figure 8. Summary of the age vs. depth relationship of the Site U1396 sediments. Paleomagnetic datums are depicted in red squares, depths are from Hatfield (2015) while ages are from Ogg et al. (2012). Nannofossil datums are depicted in blue triangles, open for secondary and closed triangles for primary. Depths for nannofossil datums are from Expedition 340 Scientists (2013) unless noted as being from Wall-Palmer et al. (2014), ages are from Backman et al. (2012). Vertical blue line denotes uncertainty in true stratigraphic position of datum. Planktic foraminifera datums are depicted in green triangles, open for secondary and closed triangles for primary. Depths are from this study, ages are from the Wade et al. (2011) astrochronological calibration. Vertical line denotes uncertainty in true stratigraphic position of datum. Black diamond denotes a ^{14}C date (Accelerator Mass Spectrometry, AMS), and yellow diamond denotes MIS 5.5 and 6/7, identified within Wall-Palmer et al. (2014). Black line depicts a linear interpolation for sediment age between paleomagnetic datums. The orange line depicts the ages from the astrochronological tuning. The brown line depicts the ages from the $\delta^{18}O$ correlation to the Marine Isotope Stages (MIS) within the LR04 benthic $\delta^{18}O$ stack (Liesecki and Raymo, 2005).

Figure 9. Summary of differences in different methods of age calculation. Orange polygon represents the difference between the astrochronological ages and the paleomagnetic age for each sample included in the isotope record. Brown polygon represents the difference between the marine isotope stage (MIS) ages and the paleomagnetic age for each sample included in the isotope record. Red horizontal lines correspond to the ages of paleomagnetic reversals (Ogg et al. 2012).

Figure 10. Summary of sedimentation rates, paleoceanographic events, and sediment character. Upper panel depicts the L* (brightness) parameter from shipboard measurements. Black line represents a 100-kyr running mean. Red dots are discrete $CaCO_3$% measurements from shipboard geochemistry. In the bottom panel, paleomagnetically derived sedimentation rates are in red (all sediment types), blue (no volcanic sediments), and purple (only volcanic sediments). MIS-age derived sedimentation rates are in orange (all sediment types) and green (no volcanic sediments). Inset depicts the correlation between L* and MIS No Volc sedimentation rates. Blue boxes represent several pertinent paleoceanographic events while grey depict climatic events (see discussion for citations and numerical dates).